TPC survey and alignment.

Yuri Fisyak

1. Introduction.

In January 2013 F.Karl (CAD, Survey and Alignment group) made new measurements of TPC wheel positions with respect to STAR magnet. During Run XIII cosmic data with two magnet polarities were taken. This gives us an opportunity to revisit TPC alignment. In this note we present:

- a review of survey analysises done so far,
- a new analysis of all survey data (2003, 2004 and 2013),
- a summary of our present understanding of TPC alignment as whole,
- a measurement of magnetic field direction in TPC using low energy ($\sim$ 10 MeV) electrons, and
- relative (sub) sectors alignment using cosmic tracks.

2. Notations.

The transformation (4D) matrix $\mathbf{R} = \mathbf{L} \to \mathbf{G}$ between local ($\mathbf{L}$) and global ($\mathbf{G}$) coordinate systems can be defined as shifts in X,Y,Z directions (x_0, y_0, z_0) and rotations around X(α), Y(β), Z(γ) axes:

$$\mathbf{R} = T(x_0, y_0, z_0) \times R_x(\alpha) \times R_y(\beta) \times R_z(\gamma) =$$

$$\begin{pmatrix} 1 & 0 & 0 & x_0 \\ 0 & 1 & 0 & y_0 \\ 0 & 0 & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & & 1 \end{pmatrix} \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} =$$

$$\begin{pmatrix} 1 & 0 & 0 & x_0 \\ 0 & 1 & 0 & y_0 \\ 0 & 0 & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\beta\,\cos\gamma & -\cos\beta\,\sin\gamma & \sin\beta & 0 \\ \cos\alpha\,\sin\gamma + \sin\alpha\,\sin\beta\,\cos\gamma & \cos\alpha\,\cos\gamma - \sin\alpha\,\sin\beta\,\sin\gamma & -\sin\alpha\,\cos\beta & 0 \\ \sin\alpha\,\sin\gamma - \cos\alpha\,\sin\beta\,\cos\gamma & \cos\alpha\,\sin\beta\,\sin\gamma + \sin\alpha\,\cos\gamma & \cos\alpha\,\cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Assuming small α, β, γ ($\sim 10^{-3}$), it can be expressed in the following way:

$$\mathbf{R} = \begin{pmatrix} 1 & 0 & 0 & x_0 \\ 0 & 1 & 0 & y_0 \\ 0 & 0 & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -\gamma & \beta & 0 \\ \gamma & 1 & -\alpha & 0 \\ -\beta & \alpha & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & -\gamma & \beta & x_0 \\ \gamma & 1 & -\alpha & y_0 \\ -\beta & \alpha & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Thus transformations from local coordinates ($\vec{\mathbf{x}}_L$) and normal to plane direction to globals ones ($\vec{\mathbf{x}}_G$ and $\vec{\mathbf{t}}_G$) are

$$\vec{\mathbf{x}}_G = \begin{pmatrix} x_G \\ y_G \\ z_G \\ 1 \end{pmatrix} = \mathbf{R}\vec{\mathbf{x}}_L = \begin{pmatrix} 1 & -\gamma & \beta & x_0 \\ \gamma & 1 & -\alpha & y_0 \\ -\beta & \alpha & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_L \\ y_L \\ z_L \\ 1 \end{pmatrix}, \vec{\mathbf{t}}_G = \begin{pmatrix} t_x \\ t_y \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & -\gamma & \beta & x_0 \\ \gamma & 1 & -\alpha & y_0 \\ -\beta & \alpha & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \beta \\ -\alpha \\ 1 \\ 0 \end{pmatrix}. \quad (1)$$

The inverse transformation ($\mathbf{R}^{-1} = \mathbf{G} \to \mathbf{L}$) is defined as

$$
\begin{aligned}
\vec{\mathbf{x}}_L &= \mathbf{R}^{-1}\vec{\mathbf{x}}_G \\
&= \begin{pmatrix} 1 & \gamma & -\beta & -x_0 \\ -\gamma & 1 & \alpha & -y_0 \\ \beta & -\alpha & 1 & -z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_G \\ y_G \\ z_G \\ 1 \end{pmatrix} \\
&= \begin{pmatrix} 1 & \gamma & -\beta & -x_0 - \gamma y_0 + \beta z_0 \\ -\gamma & 1 & \alpha & \gamma x_0 - y_0 - \alpha z_0 \\ \beta & -\alpha & 1 & -\beta x_0 + \alpha y_0 - z_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_G \\ y_G \\ z_G \\ 1 \end{pmatrix} \\
&= \begin{pmatrix} (y_G - y_0)\gamma - \beta z_G + x_G + \beta z_0 - x_0 \\ (x_0 - x_G)\gamma + \alpha z_G + y_G - \alpha z_0 - y_0 \\ z_G - \alpha y_G + \beta x_G - z_0 + \alpha y_0 - \beta x_0 \\ 1 \end{pmatrix} \\
&\approx \begin{pmatrix} (x_G - x_0) + \gamma y_G - \beta z_G \\ (y_G - y_0) - \gamma x_G + \alpha z_G \\ (z_G - z_0) + \beta x_G - \alpha y_G \\ 1 \end{pmatrix}.
\end{aligned} \tag{2}
$$

The equation

$$z_L = (z_G - z_0) - \alpha y_G + \beta x_G = 0; z_G = z_0 - \beta x_G + \alpha y_G. \tag{3}$$

will be used to fit plane position (z_0) and two angles (α and β).

The precision holes on TPC sectors, used for wheel survey, formed circles on the wheels at different radii. Fitting measurements of these holes by circles allows us to measure center of wheel (x_0 and y_0) and rotation of wheels around Z direction (γ).

3. Survey

The magnet survey contains measurement of fiducials on West and East side of magnet. For the analysis it was used fiducials on East and West face of the magnet (8 fiducials for each side).

The East and West TPC wheels survey was done using measurement of precision holes in TPC sectors mounted on the wheels. Each TPC sector has 4 precision holes: **A**, **B**,**C** and **D**. The holes were made at center of sector at 4 difference radii on external sides from TPC center. **C** holes cannot be measured because they are hidden by front-end electronics. The measurements are done with precise pin (height = 0.700±0.001”) positioned in each hole.

The membrane measurements from both sides of TPC were done using holes in aluminum strips glued to it.

The survey measurement are done in “Survey Coordinate System” (**S**). The task is to find transformation from TPC to Global coordinate system ($\mathbf{T} \to \mathbf{G}$) and transformations from East (**ET**) and West (**WT**) Tpc Half coordinate systems to TPC .

3.1. Data.

STAR survey was done 4 times:

1. 1998. The TPC was measured twice:

- once standing alone in the assembly hall, and
- once after TPC was installed in the magnet.

This survey has been used as reference for the following ones.

2. September 15-16, 2003, Magnet survey, TPC in magnet coordinate system, TPC Wheel, SVT stuff.
3. August 2004, more complete survey for Magnet, TPC and SVT[3].
4. January 2013, survey of the magnet and TPC wheels[4].

The position of TPC membrane has been measured only once in 1998 and recalculated for 2004 and 2013 surveys[2].

3.2. 1998 survey data analysises.

An analysis of 1998 data[6] gave conclusions that:

- the West wheel (**WW**) is rotated around Z axis by γ = -0.43 mrad with respect to the East wheel (**EW**)[5].
- TPC (**T**) is located at (x = -0.276 cm, y = -0.082 cm, z = -0.192 ± 0.050 cm) in the global coordinate system (**G**)[6].

One more analysis of these data[7] used averaging over all combinations of measured points and constructing their vector cross products gave measurement of direction of planes ($\vec{\mathbf{t}}_G$):

- For **TPC** alone (the 1-st survey) in Survey coordinate system (**S**):
  - East wheel: $t_x = \beta_{TPC} = -0.0304\ mrad$, and $t_y = -\alpha_{TPC} = 0.0898\ mrad$,
  - West wheel: $t_x = \beta_{TPC} = 0.0524\ mrad$, and $t_y = -\alpha_{TPC} = -0.0773\ mrad$.
- For TPC in **Magnet** (the 2-nd survey) in **S**:
  - East wheel: $t_x = \beta_{Magnet} = -0.4063\ mrad$, and $t_y = -\alpha_{Magnet} = 0.1745\ mrad$,
  - West wheel: $t_x = \beta_{Magnet} = -0.3302\ mrad$, and $t_y = -\alpha_{Magnet} = 0.0317\ mrad$,
  - The averaged for East and West wheels differences between rotation for TPC inside of Magnet and TPC alone gave rotation of TPC to Global coordinate system (**T** → **G**).
    * East wheel in **G**: $\beta = \beta_{Magnet} - \beta_{TPC} = -0.3757\ mrad$ and $\alpha = \alpha_{Magnet} - \alpha_{TPC} = -0.0847\ mrad$,
    * West wheel in **G**: $\beta = \beta_{Magnet} - \beta_{TPC} = -0.3826\ mrad$ and $\alpha = \alpha_{Magnet} - \alpha_{TPC} = -0.109\ mrad$.

The estimated values from the analysises are summarized in Table 1.

Table 1: TPC coordinate transformations from 1998 survey data analysis.

	x_0 (cm)	y_0 (cm)	z_0 (cm)	α(mrad)	β(mrad)	γ (mrad)	comment
WW → EW						-0.43	Wheel [5]
T → G	-0.276	-0.082	-0.192± 0.050				Tpc [6]
EW → G				0.08	-0.38		Wheel[7]
WW → G				0.11	-0.38		Wheel[7]
T → G	-0.276	-0.082	-0.192± 0.050	0.10	-0.38		Tpc [6] and [7]

3.3. 2004 survey data analysis.

The analysis of 2004 survey data[8] was done with assumption that TPC is a perfect cylinder with each end of the TPC is formed by 12 identical sectors. The survey targets are embedded in each sector at the same positions. In the Table 2 the original results of TPC survey analysis are presented. There is some difference from 1998 data analysis but this difference is not very drastical. In Table 3 database entries (Geometry/tpc/tpcGlobalPosition) used as global TPC position for different run periods and the results of above analysises are presented. The survey results (**T** → **G** with assumption **S** == **G** from Table 2) were used for Y2004 data. For unknown reasons this TPC global position in database has been changed in Y2005 and again more drastically (TPC was moved down by ≈ 0.4 cm) in Y2006.

Table 2: TPC rotation parameters from 2004 survey analysis.

	x_0 (cm)	y_0 (cm)	z_0 (cm)	α(mrad)	β(mrad)	γ (mrad)	comment
WW → **G**				-0.127	-0.321		**S** == **G**
EW → **G**				0.039	-0.376		**S** == **G**
T → **G**	-0.252	-0.175	-0.205	-0.044	-0.345		East and West average[8]

Table 3: TPC rotation parameters from 1998 and 2004 analysises and parameters from MySQL Database used in reconstruction so far.

	x_0 (cm)	y_0 (cm)	z_0 (cm)	α(mrad)	β(mrad)	γ (mrad)	comment
T → **G**	-0.276	-0.082	-0.192± 0.050	0.10	-0.38		1998, Tpc [6] and [7]
Y2000	-0.276	-0.082	-0.192	-0.156	-0.381	0.04	∼1998, DB entry
T → **G**	-0.252	-0.175	-0.205	-0.044	-0.345		East and West average[8]
Y2004	-0.252	-0.175	-0.205	-0.044	-0.345	0	2004, DB entry
Y2005	-0.222	-0.143	-0.209	-0.132	-0.441	0.04	≈2004, DB entry
Y2006	-0.180	-0.6752	-0.08086	-0.044	-0.1897	0.9622	unknown, DB entry
Y2010	-0.178	-0.6752	-0.08086	-0.044	-0.1897	0.9622	unknown, DB entry
Y2010-02	-0.180	-0.6752	-0.08086	-0.044	-0.1897	0.9622	unknown, DB entry
Y2011	-0.178	-0.6752	-0.08086	-0.044	-0.1897	0.9622	unknown, DB entry

3.4. The present analysis

In the present survey data analysis we use measurement of fiducials and form a plane (z_0, α, β) by fitting fiducial measurement with eq.3. The measurements of TPC precision holes in the corresponding wheel coordinate system were fitted by circle for each ring (**A**, **B**, and **D**), and centers of circle and offsets in ϕ with respect to nominal sector position were estimated. Using the plane parameters we formed transformation matrices between different system of coordinate. This procedure was iterative and below we present the result of the last iteration. The previous note on the 2003 and 2004 TPC survey data analysis with this approach can be found in [1]. The difference between the present and previous analysis is that now we use the East Wheel as reference for the TPC coordinate system instead of average of East and West wheels used previously.

3.4.1. Magnet

For STAR magnet survey we used 8 fiducial marks on West (WF) and East (EF) sides. The results of magnet fiducial marks fits for plane are presented in Table.4.

Observations is the same as in previous analysis of 2003 and 2004 data [1]:

1. The West and East Magnet fiducials form planes with average out of plane residual ~130 μm.
2. Differences between 2003, 2004, and 2013 surveys are rather small (~ 50μm in z and ~ 0.02 mrad in α and β). Thus we have very good reproducibility of survey measurements.
3. Survey system is not the same as magnet system but their differences are rather small (a shift ~300 μm in Z and ~0.1 mrad in angles). We apply shift in Z and ignore all rotations as a transformation from Survey to Magnet coordinate systems ($\mathbf{S} \rightarrow \mathbf{G}$) .

Table 4: The results of 2003, 2004,and 2013 data analysis for West and East Magnet planes in Survey Coordinate system.

target	z_0(cm)	α (mrad)	β (mrad)	Out plane RMS (μm)
2003,WF 1-8	362.5027 ± 0.0030	-0.15 ± 0.02	-0.04 ± 0.01	130.2
2003,EF 1-8	-362.5545 ± 0.0647	0.12 ± 0.50	-0.07 ± 0.12	96.2
2003.Average	-0.0259	-0.01	-0.06	
2004,WF 1-8	362.4907 ± 0.0030	-0.20 ± 0.02	-0.04 ± 0.01	139.5
2004,EF 1-8	-362.5550 ± 0.0647	0.12 ± 0.50	-0.07 ± 0.12	95.8
2004,Average	-0.0322	-0.04	-0.06	
2013,WF 1-8	362.5011 ± 0.0041	-0.16 ± 0.03	-0.05 ± 0.01	128.4
2013,EF 1-8	-362.5550 ± 0.0065	0.12 ± 0.05	-0.07 ± 0.01	95.8
2013,Average	-0.0269 ± 0.0038	-0.02 ± 0.03	-0.06 ± 0.01	

3.4.2. TPC coordinates system.

The results of fit TPC planes (West and East wheels, membrane measured from West and East sides) are presented in Table 6. The circle fit of sector holes is presented in Table 7. All measurements form planes with out of plane r.m.s. ~ 200 μm, including 1998 measurement of membrane. The position of wheel plane in TPC (from TPC drawings) is Z = 229.71 cm. The height of survey probe is (0.7±0.001) inches = 1.7780±0.0025 cm (Frank Karl has confirmed this). The difference in measured length between wheels and expected value

$$dZ = (Z_{West} - Z_{East})/2 - 229.71 - 1.7780$$

is shown in the table 6 and it is $\approx -70\mu m$. This $\approx$ -70μm difference could be interpreted as a possible systematic error in the measurements. The membrane thickness ($Z_{West} - Z_{East}$) = 710 μm is a factor of 10 bigger than real thickness of 70 μm (NIM A 499 (2003) p. 661). This difference is still puzzle us. We assume that this came from some 1998 measurement problem.

From the table 6 we define the TPC coordinate system as the 2013 east wheel plane shifted by 229.71 + 1.7780 cm, which is coming from TPC drawings and size of the survey probe. From this table it is clear that the choice of the East wheel as a reference for TPC coordinate system was successful. All rotations are within ~ 0.2 mrad.

Comparing parameters of $\mathbf{T} \rightarrow \mathbf{G}$ transformation from the present and previous analysises (Table 5) we can conclude that:

Table 5: TPC coordinate transformation to Magnet.

	x_0 (cm)	y_0 (cm)	z_0 (cm)	α(mrad)	β(mrad)	γ (mrad)	comment
T → **G**	-0.276	-0.082	-0.192± 0.050	0.10	-0.38		1998, [6] and [7]
T → **G**	-0.252	-0.175	-0.205	-0.044	-0.345		2004, [8]
2003,**T** → **G**	-0.2686	-0.1590	-0.1775	-0.04	-0.46	0.36	present
2004,**T** → **G**	-0.2355	-0.1375	-0.1796	0.10	-0.55	0.52	present
2013,**T** → **G**	-0.2383	-0.1732	-0.1957	0.10	-0.48	0.36	present
2003,**G** → **S**			-0.0259				present
2004,**G** → **S**			-0.0322				present
2013,**G** → **S**			-0.0269				present
2003,**WW** → **T**	0.0393	-0.0305	231.4759	0.13	0.12	-0.39	present
2004,**WW** → **T**	0.0330	-0.0092	231.4805	0.08	0.10	-0.37	present
2013,**WW** → **T**	0.0193	-0.0133	231.4724	0.16	0.11	-0.39	present
2003,**EW** → **T**			-231.4880	-0.00	-0.00	0.04	present
2004,**EW** → **T**		-0.0001	-231.4829			0.05	present
2013,**EW** → **T**			-231.4880	-0.00	-0.00	0.03	present
2003,**WT** → **T**	0.0393	-0.0305	-0.0121	0.13	0.12	-0.39	present
2004,**WT** → **T**	0.0330	-0.0092	-0.0075	0.08	0.10	-0.37	present
2013,**WT** → **T**	0.0193	-0.0133	-0.0156	0.16	0.11	-0.39	present
2003,**ET** → **T**				-0.00	-0.00	0.04	present
2004,**ET** → **T**		-0.0001	0.0051			0.05	present
2013,**ET** → **T**				-0.00	-0.00	0.03	present

Table 6: Result of planes fit in TPC coordinate system.

	z_0 (cm)	α(mrad)	β(mrad)	residual (μm)	comment
2003,**WW** → **T**	231.4759±0.0034	0.13±0.05	0.12±0.05	0.7±188.9	Wheel
2003,**EW** → **T**	-231.4880±0.0006	-0.00±0.01	-0.00±0.02	103.4±174.3	Wheel
2004,**WW** → **T**	231.4805±0.0034	0.08±0.05	0.10±0.05	0.6±188.0	Wheel
2004,**EW** → **T**	-231.4829±0.0006	0.00±0.01	0.00±0.01	98.0±182.2	Wheel
2004,**WM** → **T**	0.0744±0.0003	-0.09±0.00	0.12±0.00	14.6±176.3	Membrane
2004,**EM** → **T**	0.0036±0.0003	-0.13±0.00	0.02±0.00	-9.0±139.2	Membrane
2013,**WW** → **T**	-231.4829±0.0006	0.00±0.01	0.00±0.01	98.0±182.2	Wheel
2013,**EW** → **T**	231.4724±0.0019	0.16±0.02	0.11±0.02	-35.2±198.9	Wheel
2013,**WM** → **T**	0.0619±0.0010	-0.10±0.01	0.07±0.01	4.3±173.4	Membrane
2013,**EM** → **T**	-0.0091±0.0008	-0.12±0.01	0.00±0.01	-4.1±137.9	Membrane

Table 7: Result of fit sector precision holes by rings in Wheel Coordinate systems.

year,Ring	x_0 (cm)	y_0 (cm)	R (cm)	γ (mrad)
2003, WA	0.0006± 0.0020	-0.0029± 0.0015	54.5509± 0.0012	0.02± 0.03
2003, WB	0.0011± 0.0019	-0.0059± 0.0015	118.7541± 0.0012	-0.01± 0.02
2003, WD	-0.0018± 0.0032	0.0089± 0.0023	190.5694± 0.0020	-0.00± 0.02
Average	0	0		0
2003, EA	0.0029± 0.0011	0.0035± 0.0009	54.5577± 0.0007	0.03± 0.03
2003, EB	0.0028± 0.0014	-0.0011± 0.0010	118.7556± 0.0008	-0.01± 0.02
2003, ED	-0.0056± 0.0018	-0.0026± 0.0014	190.5796± 0.0011	-0.03± 0.02
Average	0	-0.0001		0
2004, WA	0.0004± 0.0020	-0.0028± 0.0015	54.5506± 0.0012	0.02± 0.02
2004, WB	0.0015± 0.0019	-0.0055± 0.0014	118.7537± 0.0012	-0.02± 0.02
2004, WD	-0.0019± 0.0031	0.0084± 0.0022	190.5686± 0.0019	-0.01± 0.02
Average	0	0		0
2004, EA	0.0023± 0.0010	0.0033± 0.0008	54.5577± 0.0006	0.04± 0.03
2004, EB	0.0028± 0.0013	0.0002± 0.0010	118.7563± 0.0008	-0.00± 0.02
2004, ED	-0.0051± 0.0017	-0.0034± 0.0013	190.5793± 0.0011	-0.02± 0.02
Average	0	0		-0.01
2013, WA	-0.0002± 0.0042	-0.0019± 0.0044	54.5527± 0.0030	0.02± 0.03
2013, WB	0.0005± 0.0041	-0.0056± 0.0041	118.7558± 0.0029	-0.02± 0.02
2013, WD	-0.0003± 0.0060	0.0075± 0.0053	190.5705± 0.0041	-0.01± 0.02
Average	0	0		0
2013, EA	0.0048± 0.0041	0.0042± 0.0041	54.5589± 0.0029	0.04± 0.03
2013, EB	-0.0008± 0.0042	-0.0016± 0.0044	118.7620± 0.0030	-0.01± 0.02
2013, ED	-0.0040± 0.0063	-0.0027± 0.0047	190.5802± 0.0038	-0.02± 0.02
Average	0	0		0

- shift in X, Y and Z are rather close to each other (~ 0.04 cm, 0.1 cm and 0.02cm, respectively),
- difference in rotations around X and Y are ~ 0.2 mrad,
- the present analysis shows that TPC as whole is rotated ~ 0.4 mrad around Z and keeps difference between West and East rotation ~ 0.42 mrad.

References

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